Unmanned Sea Surface Vehicle (USSV) Motion Data and Refueling Equipment Design

Bob Galway, Mechanical Engineer
Naval Surface Warfare Center
Carderock Division, Detachment Norfolk
Code 232-Systems Design &Integration
Little Creek Amphibious Base
2600 Tarawa Court, Norfolk, VA. 23521-3239
Robert.Galway@navy.mil

Barney Harris, Mechanical Engineer
CDI Marine
2624 South Ives Street
Arlington, VA 22202
Donald.Harris@cdicorp.com

Abstract:

A key design challenge in at-sea refueling and recovery of Unmanned Sea surface Vehicles (USSVs) is making a connection with the USSV to the towed sled, in view of relative motions between the two. To enable a reliable connection, the USSV must be capable of positioning its bow within the sled's docking aperture. The level of confidence is traded off against size and acceptable sea state operating range for recovery and refueling equipment. NSWC Carderock Division Detachment Norfolk performed at-sea experiments designed to acquire real world, statistically significant data to determine the ability of an autonomous USSV to hit a target under a variety of operational conditions including sea state, heading relative to the sea, and USSV speed. The resulting extensive set of motion and positional data will be useful for future system designers for years to come. This work was funded by the Office of Naval Research, Sea Platforms and Weapons Division.

NSWC Carderock Division Detachment Norfolk has developed a system to enable underway refueling of USSVs in open ocean conditions that does not require recovering the USSV. This concept relies on a two-part connection, the initial latching of the USSV to a towed sled, and a fluid seal. The capture and fueling system consists of an extendable probe in the USSV's bow that engages a receiving mechanism mounted in the vertex of a V-shaped sled. The sled is towed by a host vessel and intended to act as a deployable refueling station from a mother ship. In use, the USSV will approach the sled from astern and autonomously navigate into the sled's notch, make a mechanical connection, verify the fluid path and seal integrity, receive fuel, and then disconnect, steer clear, and then continue with its mission. The probe is fully retractable, fits inside a removable section of the USSV's bow, and has minimal hydrodynamic impact on the USSV performance.

1.0 Introduction

The Naval Surface Warfare Center Carderock Division (NSWC CD) det Norfolk has been engaged in development of launch and recovery systems for small craft for many years. Most recently NSWC CD det Norfolk has partnered with Office of Naval Research (ONR) Code 33 in a multi-year incremental development of systems for recovering and refueling Unmanned Sea Surface Vehicles (USSVs) in support of expected future needs of the fleet. NSWC CD initially conducted broad investigations of many different system concepts to make an initial connection. These included probes, hooks, and latches installed on small boats interacting with towed apparatus including lines, funnels, nets, spreaders, and a variety of drogues'[1]. From this work it was determined that the bow latch offered the greatest potential. NSWC CD then developed latch mechanisms for autonomous recovery of USSVs. The second increment involved development of an autonomous probe/receiver/sponson latch concept with a connection style that lent itself to refueling remote from the host vessel. A third increment used the probe/receiver/sponson connection style and added a hose pushing device that autonomously put a

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **2010**	2. REPORT TYPE		3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Unmanned Sea Surface Vehicle (USSV) Motion Data and Refueling Equipment Design**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center Carderock Division,Code 232-Systems Design &Integration,2600 Tarawa Court,Norfolk,VA,23521-3239**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR’S ACRONYM(S)
			11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES **Launch & Recovery Symposium 2010, Dec 8-9, 2010, Arlington, VA**			
14. ABSTRACT **A key design challenge in at-sea refueling and recovery of Unmanned Sea surface Vehicles (USSVs) is making a connection with the USSV to the towed sled, in view of relative motions between the two. To enable a reliable connection, the USSV must be capable of positioning its bow within the sled?s docking aperture. The level of confidence is traded off against size and acceptable sea state operating range for recovery and refueling equipment. NSWC Carderock Division Detachment Norfolk performed at-sea experiments designed to acquire real world, statistically significant data to determine the ability of an autonomous USSV to hit a target under a variety of operational conditions including sea state, heading relative to the sea, and USSV speed. The resulting extensive set of motion and positional data will be useful for future system designers for years to come. This work was funded by the Office of Naval Research, Sea Platforms and Weapons Division. NSWC Carderock Division Detachment Norfolk has developed a system to enable underway refueling of USSVs in open ocean conditions that does not require recovering the USSV. This concept relies on a two-part connection, the initial latching of the USSV to a towed sled, and a fluid seal. The capture and fueling system consists of an extendable probe in the USSV’s bow that engages a receiving mechanism mounted in the vertex of a V-shaped sled. The sled is towed by a host vessel and intended to act as a deployable refueling station from a mother ship. In use, the USSV will approach the sled from astern and autonomously navigate into the sled?s notch, make a mechanical connection, verify the fluid path and seal integrity, receive fuel, and then disconnect, steer clear, and then continue with its mission. The probe is fully retractable, fits inside a removable section of the USSV?s bow, and has minimal hydrodynamic impact on the USSV performance.**			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**18**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

hose in the tank of a USSV from a host vessel and permitted fluid transfer to occur. To our knowledge, this was the first autonomous refueling concept for USSVs actually demonstrated at sea with testing. The fourth increment of development came as the result of an in process testing observation made during latch testing that suggested that apart from vendor's claims about sensor capability, very little data existed documenting how closely a USSV could be delivered to a desired point while operating at speeds and conditions expected for recovery operations. This increment collected data about the ability of a USSV to consistently deliver a point on its bow to a specific location on a towed target. The fifth increment is the development and testing of a single point connection capable of permitting autonomous USSV connection for recovery or refueling. This increment is the manifestation of two evolutionary design iterations from the concept described in the second increment and lessons learned from analysis of data from the fourth increment. The new probe/receiver/sponson concept was scaled to fit in the bow plug (removable section of USSV bow) of an existing USSV and offer no hydrodynamic resistance as it fully retracts into the bow plug of the USSV, and with a smaller sponson is capable of being stored in a 20' container and launched from a host ship. This paper discusses the fourth and fifth increments of the NSWC CD det Norfolk and ONR Code 33 USSV autonomous recovery and refueling development effort.

2.0 USSV simulated recovery data collection effort

There is no escaping the reality that any recovery of a craft at sea while both craft and host ship are underway results in a collision between craft and host ship. The severity of this collision and whether or not there is damage on both vehicles is determined by many factors including the state of relative dynamic motion between the two bodies at the time of recovery. One of the challenges in designing USSV recovery equipment is to quantify the dynamic conditions present at recovery into usable design parameters[2]. Data describing craft performance is available, but the characteristics of low speed operation in the wake of a larger boat are not well documented. Another challenge is to quantify the ability of a USSV to get to a desired point behind a parent ship to permit refueling or recovery from a larger parent ship. In the current design for USSV recovery, the craft's command and control system (sensors, mission computer, steering) capability determines how close the USSV gets to the desired point, then a mechanical guide provides the final connection for a latch, grab or recovery. The size of the final mechanical guide is proportional to the ability of the USSV to get to the desired point behind the parent craft for a recovery or refueling evolution. At present there is not a great deal of quantitative data available that describes the ability of a USSV to hit a towed target while underway at launch and recovery speeds and conditions, although several studies describing connection percentages have been accomplished. At present, no known closed analytical solution for USSV craft motion in the environment behind a large ship travelling a less than 10 knots is available. The breadth of environmental factors such as waves, wind, current, and parent craft wake associated with normal naval operations makes the expectation that such a solution will be achieved near-term unlikely. However, empirical information from test data taken during simulated recovery conditions are an achievable target and important to support engineering development of future systems to meet these objectives.

In FY2008 a database of empirical information was started by NSWCCD by using the USSV High Tow Force (HTF) to try and hit a towed recovery point for a variety of tow speeds, approach speeds, and sea headings. The proposal included the synthesis and development of a method for measuring the distance between two moving craft in dynamic seas with a high degree of fidelity to determine how well a USSV was able to navigate to a moving target point and then use it to collect data

from a USSV in a variety of operational conditions designed to replicate conditions experienced during recovery and refueling operations. Such a collection of data could then be analyzed by researchers and design engineers to predict dynamic conditions and make informed design decisions for systems and equipment relating to autonomous recovery or refueling. This type of information could be used to formulate solutions for a smart USSV handling system using advanced knowledge of on-coming waves and craft controls system elements. The same information could be used to optimize structural design of USSV hull or host ship bunking systems to survive the repeated impacts. This data collection effort differed greatly from prior latch testing efforts, where the recovery line was presented in the plane of the water and the recovery percentage determined mostly by the pitch angle of the USSV at the time the latch mechanism intersected the recovery line. General craft motions in these efforts were not recorded, only capture percentages. The 2008 effort did not use latching as a criteria, but instead captured motion data on both the USSV and target craft in 6 degrees of freedom (including the pitch of both craft) and position location data from a high fidelity Real Time Kinetic (RTK) GPS system to determine craft motions and ability to hit a towed point while underway. The ultimate goal for this data is to assist DoD researchers and engineers with modeling and simulation efforts in the area of USSV launch and recovery.

2.1 Relative craft position measurement method

USSVs that are involved in recovery or refueling operation will typically have some form of short range sensing system as part of their overall control system for positioning relative to a parent craft or target. In the case of the USSV HTF used for this data collection effort, a short distance positioning system based on radar principles is used by the USSV HTF for close proximity relative positioning. The sensing system is advertised to have a +/- 0.5 m accuracy capability. However, to validate this claim when these sensors are used aboard a USSV, a second more precise measuring system needed to be developed. This challenge was met using a Real Time Kinetic (RTK) distance measuring system designed for use as a survey instrument. The system was implemented by fitting both the USSV and the tow target with measuring sensors in the bow and stern. These sensors were advertised to provide centimeter accuracy in surveying situations and had the capability of providing a vertical location in addition to longitude and latitude. The manufacturer claimed accuracy on the order of 1 cm for horizontal and 1.5 cm accuracy in vertical measurements in RTK mode, with proper signal. Using information recorded by these sensors, the relative position of target points was determined. In addition to the position sensors, both craft were fitted with motion sensors to record motion during all runs. Key environmental factors such as wind speed, current, and sea heading were recorded for the parent craft. All the information was time stamped and recorded on a data logger. Due to the desired fidelity of data, the frequency of collection was high, resulting in many points being taken each second.

This was a new method of validating position between two small craft while underway and presented many hardware and software challenges. There were in excess of 100 data fields collected and although sensors transmitted data at different frequencies, the data collection rate was set to the highest input frequency. Each run lasted for several minutes, thus resulting in very large data files. There were issues with signal RTK system signal quality that seemed to be affected by the craft motion, cloud cover, and battery strength. However, with adequate compensation for these issues the method proved to be accurate enough to achieve the validation goal.

2.2 Simulating Recovery and Refueling operations for Data collection

Simulation of USSV motions similar to what is expected during real recovery and refueling operations was accomplished by towing a target 100 feet behind a parent craft at tow speeds, current headings, and USSV approach speeds expected during real recovery and refueling operations with the host ship. The towed target carried the transponders used by the short distance positioning system to communicate with the USSV interrogator and guide the USSV to the intended position. A run typically started about 100 meters behind the tow craft where a seek command was sent to USSV control system initiating autonomous target acquisition. The USSV then proceeded to hit the target point until a pre-set safety distance was reached, stopping the seek function, to prevent actual impact between USSV and target craft. This distance varied slightly between 17 and 20 meters, as determined by the test director. The seek command for the USSV was then disabled and the USSV allowed to drift back and control transferred to the coxswain. All the positional and motion data for both target craft and USSV were recorded and the minimum lateral and vertical distances from target, as well as over-shoot or undershoot were calculated.

The simulated recovery runs were accomplished at the extreme ends and middle of expected likely range of USSV target tow speeds, sea headings, and approach speeds. Twenty seven variations of the test runs were created by all combinations of the three tow speeds, (6, 8, &10 knots), three sea headings (into the seas, with the seas, and beam seas), and three approach speeds (1 m/s, 10.5 m/s, and 2 m/s faster than the relative speed of the tow sled). A total of 10 runs for each of the 27 variations yielded a total of 270 autonomous runs. In addition to the autonomous runs, each variation was attempted by a skilled coxswain for comparison. Table 1 provides a summary of averages for various parameters.

Test Variation	***Average Lateral Relative Difference*** *(Meters)*	***Average Vertical Relative Difference*** *(Meters)*	***Average Over-shoot*** *(Meters)*	***Average Under-shoot*** *(Meters)*
Following Seas	*.507*	*1.261*	*2.315*	*.034*
Beam Seas	*.413*	*1.212*	*1.669*	*.004*
Head Seas	*.538*	*1.217*	*1.343*	*.269*
6 Knot Tow Speed	*.414*	*1.426*	*2.414*	*.004*
8 Knot Tow Speed	*.665*	*1.191*	*1.478*	*.032*
10 Knot Tow Speed	*.408*	*1.056*	*1.213*	*.275*
1 m/s relative Approach Speed	*.466*	*1.254*	*1.702*	*.016*
1 .5 m/s relative Approach Speed	*.515*	*1.155*	*1.618*	*.023*
2 m/s relative Approach Speed	*.478*	*1.267*	*1.829*	*.305*

Table 1. USSV data collection results by test parameter variation

2.2 Data Analysis

Analysis of data collected was accomplished by two separate methods. The initial analysis yielded some results and questions that prompted a second validation analysis. For purposes of clarity from this point forward, the first analysis will be referred to as “First Analysis” and correspondingly the second as the “Second Analysis”. The large differences between the two analyses are in coordinate systems chosen

as reference point used to determine distance from USSV to target and the software used for the analysis. Specifically, the First Analysis followed a Lagrangian method in which the location of a point on one was determined in the moving coordinate system of the second. In the Second Analysis an Eulerian approach was used in which both craft motions were viewed in the global coordinate system of xyz=North, East, and Down to center of earth (NED).

The First Analysis solely looked at a difference between two virtual points, the first a set distance off the bow of the USSV and the second off the stern of the target craft. The Second Analysis considered the difference in center of gravity (CG) between the two craft and the difference between two simulated collision points (CP), or points where the vertical plane on the centerline meets the plane of the water on the bow of the USSV and on the stern of the target craft and a controlled collision would occur during recovery. The difference in CGs would indicate relative position excluding craft rotations and the difference in CPs would include the effect of the rotations of both craft, providing a minimum actual distance between craft. The intention of the Second Analysis was to validate the First Analysis, but due to mathematical modeling and software differences, an exact side-by-side comparison of values was not possible. However, both analyses independently indicated about the same average lateral relative difference.

In the First Analysis, a total of 144 test runs were identified as usable from the original 306 runs attempted. The criteria for selection was based on a quality of signal indication from the RTK system. Signal quality was a vendors measure of probability of introduced error from the RTK system momentarily losing its fix (The RTK system limitations are one of the lessons learned as a part of this effort). These 144 run attempts were selected at the simulated latch distance: when the average short distance positioning system transponder range was less than or equal to 15 meters. It should be clearly understood that these 144 run attempts were a snapshot in time when the control algorithm had determined that the USSV had reached its target and ceased to send any further throttle commands. However, in many instances the momentum of the USSV-HTF and/or wave impulse carried the USSV-HTF further forward.

The Second Analysis had benefit of being able to review results from the First Analysis and was partially motivated by the desire to reclaim some of the benefit from the data discarded by the first analysis due to loss of RTK signal. This was done by supplementing statistical data with a quality measure based on the known measured distance between sensors on each craft. The general method involved establishing a CG position in Global Coordinates (GC) based on reported RTK sensor positions and prior knowledge of where the CG of the craft was located in the local coordinate system (drawings or lift test). With this information, the distance from CG to a simulated collision point (CP) on each craft in GC could be calculated. Since the short distance positioning system seeking was stopped at some defined Latch Length (LL) of about 15 m, the CPs were adjusted such that a simulated collision would occur at LL and various distances of interest were calculated. Chief distances of interest were lateral difference in plane of water between points, vertical distance between points, and overshoot or undershoot.

Although two separate analyses were accomplished and direct comparison was not possible, the results for both analysis were similar. The results presented here reflect actual findings of the second analysis.

2.2 Summary of Data Collection Results

2.2.1 *Distance from target point*

Of primary concern to this investigation is the ability of the USSV HTF to hit the simulated target point it was seeking. Thus the first measurement considered is the lateral distance (Port or Starboard) that the USSV target point is off the towed target point at the time a collision between target points would occur. To get the distance at the desired point, a vector between craft CGs was calculated and when magnitude of the lateral and longitudinal components of this vector equaled the target distances corrected for relative position between target points and respective craft CGs, the magnitude of the lateral offset of target points was collected. Similarly, the vertical distance between collision points was collected at the same point. Table 1 shows finding for various combinations. The overall average of lateral offset was 0.473 m and the average relative difference in vertical distance between the two points was 0.982 m.

Included in the table is a value identified as RTK Error Distance (RTK Err Dist) which came as a result of a validation effort for the preliminary data. This is in contrast to the method used in the First Analysis, which excluded data points of insufficient Horizontal dilution of precision (HDOP) value resulting in elimination of about 60% of the data. This statistic is intended to provide an indication of how much error is associated with the RTK sensor readings during a given run. It is simply a distance associated with the distance between sensors and point of concern multiplied by the fractional error from the RTK readings. Since the actual distance between sensor pairs on each craft is known, the true magnitude of the vector length between sensors is known. This value is then compared to same distance calculated from sensor data. A percent difference is obtained. This value was then multiplied by the distance from short distance positioning system sensors to the collision point on each craft. The sum of these two values was then divided by the known vector length at the collision point, yielding a fraction representative of total vector error between points. This fraction was then multiplied by the parameter of concern to get an approximated error caused by sensor error. This statistic is provided to give researchers an indication of RTK sensor error on all reasonable points, independent of HDOP value. In this instance a reasonable data point was determined by a manual review of the curve and magnitudes of each data run.

2.2.2 *Overshoot/Undershoot*

Also of concern in this investigation is the ability to control the deceleration rate of the craft to prevent overrun of a potential refueling platform receiver or recovery device. The data collected is intended to capture USSV momentum characteristics relative to deceleration at the 27 test variations, but in the balance is the test crew’s need to prevent actual impact between the USSV and the target boat. In the Throttle Control Algorithm Section of this report, there is discussion about the zones where relative speed of the USSV was adjusted to suit the test matrix, but in the last 50 meters the relative difference was always set to 0.5 m/s greater than that of the tow boat. So what we captured is effectively the remaining momentum of the USSV traveling at an approach speed identified in the test matrix and a controlled forward speed of 0.5 m/s. This speed would continue in test run until the pre-set Latch Length distance was reached and the throttles cut back and boat steered away for the next run. Overall, the USSV slightly overshot 94% of the time, with an average overshoot of 1.824 meters. Six percent of the time an undershoot occurred, the average undershoot was 0.359 m.

3.0 Development of the Single point Connection refueling device

The final increment of the NSWC CD det Norfolk and ONR Launch and Recovery development effort uses prior work and test efforts to move from the conceptual early refueling device design to a single point connection refueling system design and finally to a developmental system that can be fully integrated into an existing USSV. The NSWC CD det Norfolk & ONR C33 development team developed a concept for at-sea, underway refueling of USSVs as part of the FY07 effort. This conceptual refueling device used a large inflatable sponson and required external mounting on a USSV. This was functional for connection as demonstrated in the probe/sponson connection testing and the hose pusher refueling test. However the hydrodynamic penalty for this device was severe and it required two connections for refueling. Conceptual re-design occurred in the FY2008 NSWC CD det Norfolk and ONR partnership that created a virtual model of a retractable probe capable of being enclosed in a bow section[2]. However this design was still too large to fit in the existing bow section of a USSV. Yet, the concept showed the most promise and was choice of a 2009 refueling concept design down-select for further development. The NSWC CD det Norfolk and ONR C33 development team, along with our contractor design team has moved forward with the design, fabrication, and testing of a single point connection and refueling concept that can be fitted in an existing bow plug and fully integrated into a current USSV design. This concept relies on a two-part single point connection, the initial latching of the USSV to a towed sled, and a fluid seal. The capture and fueling system consists of an extendable probe in the USSV's bow that engages a receiving mechanism mounted in the vertex of a V-shaped sled. The sled is towed by a host vessel and intended to act as a deployable refueling station from a mother ship. In use, the USSV will approach the sled from astern and autonomously navigate into the sled’s notch, make a mechanical connection, verify the fluid path and seal integrity, receive fuel, and then disconnect, steer clear, and then continue with its mission. The probe associated with this concept is fully retractable, can be fitted inside a removable bow plug section of the USSV’s hull, and will have minimal hydrodynamic impact on the USSV hull.

This system was developed to investigate alternatives to the current refueling practice that requires a USSV to be recovered from the sea and lifted aboard the host vessel. Recovering USSVs always entails some risk of personnel injury and/or damage to the host vessel and USSV. During recovery the host vessel may be restricted in course and speed, unable to launch and recover other USSVs, and not able to operate other sensors or weapons systems, leaving it open to attack. If the host vessel can only launch/recover one USSV at a time (as is typically the case), this creates a queuing problem for groups of USSVs and subtracts from the total mission time available as all must wait while each unit is replenished and re-launched before returning to the mission area[2].

The sled based refueling system could be arranged to not interfere with the host vessel’s launch and recovery systems once deployed. The sled can be towed at any attitude to the wind and seas and will not prevent the use of the host vessel’s weapons or sensors and leaves the host vessel better able to defend itself. Multiple sled refueling systems can be employed to simultaneously refuel any number of USSVs, minimizing turnaround time. Finally, and perhaps most importantly, the sled is engineered, designed, and constructed specifically to recover USSVs in an open ocean environment, having features, materials, and controls that reduce the likelihood and consequences of collision, enabling operations to proceed in arduous weather and sea conditions.

Connecting to a USSV or manned vessel at sea presents a challenging positioning control problem. The USSV typically will have limited ability to control its position, or more accurately, heading and speed, due to the generally inadequate control authority at slow speeds provided by rudder(s)

sized and a hull form optimized for high speed compounded by limited precision and latency in throttle and rudder actuation. External influences from wind & sea conditions frequently saturate and can occasionally over power the USSVs ability to compensate. On top of it all is the limited accuracy available from and latency inherent in relative position feedback from GPS or other open sea navigation systems.

Each of these factors was considered in formulating the connection system approach which is presented graphically in figure 1. As shown, the USSV will transit to the vicinity of the sled under its own propulsion and navigation systems. Once nearby the USSV's heading and throttle commands will be arranged to bring the bow into the open "V" of the towed sled and within range of the local navigation system. The local system could comprise one or a combination of electronic, acoustic, or optically based systems that will have reliably smaller latency and relative positioning accuracy sufficient to enable the USSV to navigate its bow into the sled's notch. Once the USSV is within the sled's notch the control gradually transitions, first from the algorithm based system responding with throttle and rudder actions next to remotely sensed measurements, then to one of physical interaction between the USSV and sled, followed by the probe and funnel guide, probe and receiver, and finally the probe and receiver latch mechanism. This stepped method of bringing one craft into a local navigation system followed by several successively narrower mechanical guide stages is not a new concept, however the implementation has a plethora of design features that make it unique.

3.1 The Towed Sled USSV Refueling System

System comprises a USSV equipped with retractable refueling probe system, a towed sled with receiver mechanism, and a host vessel and is presented in Figure 1.

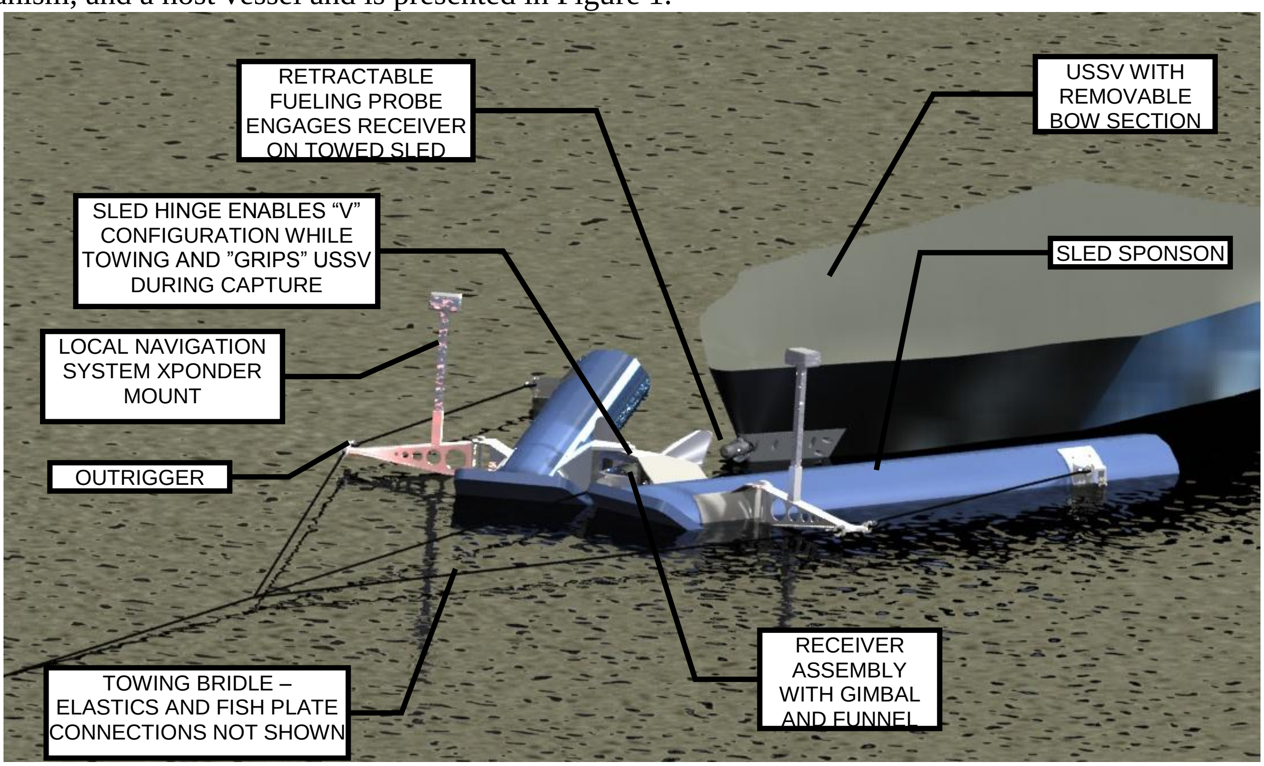

Figure 1. The Refueling System Comprises a Bow Mounted Retractable Probe Latching into a Towed Sled

3.2 USSV & Extendable Probe

The USSV probe design was required to fit within the space of an existing removable bow section of the US Navy's prototype USV. This requirement drove facets of the design to its current form. The probe system is shown in the removable bow section in Figure 2.

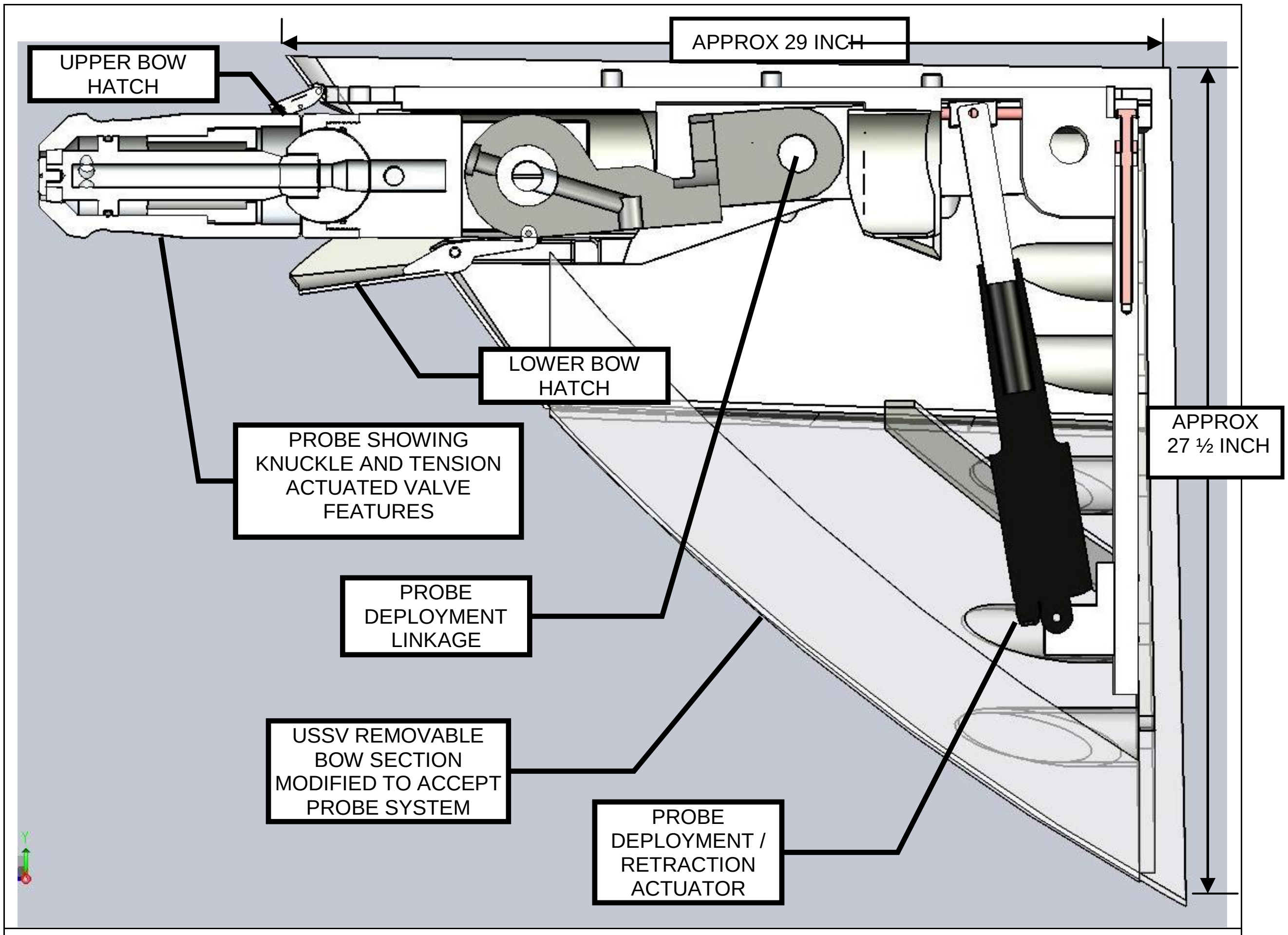

Figure 2. Cut Away View of the Refueling Probe System Mounted into the USV's Removable Bow Section.

3.3 Extend and Retract Mechanism

The probe is designed to mechanically extend for refueling and to retract to leave the USSV's hull external geometry unchanged. A small recirculating ball electrically powered actuator with pantograph mechanism–linkage is employed to extend and retract the probe. These components are fabricated from aluminum alloy and are configured to have all links in line when fully extended so the actuator only stabilizes the system and does not see any impact, connection, or towing forces. The actuator employed is a water proof off- the-shelf powerboat trim tab unit. Filament wound water lubricated bearings and bushings are employed at each hinged connection and arranged so no metal to metal sliding contact occurs. These bearings have compressive strengths close to the aluminum and are well matched.

3.4 Bow Opening Closures

The system includes small hatches that cover the probe opening in the bow section to maintain the USSV's hydrodynamics when not in use. These hatches are pushed open by probe when it is extended and close under spring force when the probe is retracted. Hatches are designed to break away in the event of a fouling event and are easily replaced with hand tools.

3.5 Probe Features

The probe contains a towing tension actuated valve in its extreme forward end that is arranged to automatically close via spring force in the event the latch connection is lost. This feature will minimize the quantity of spilled fuel to a negligible amount. Approximately 120 pounds of towing force is required to fully open the valve.

The exterior of the probe is fitted with an annular groove at its forward end. This groove is precision machined to accept balls used to capture the probe and fully described later. The probe end is spherical in shape at its forward end and tapers gradually to maximum diameter where it makes contact with the receiver. The combination of spherical end and the taper prevents binding when inserted only a small amount.

The middle of the probe is fitted with a knuckle that comprises a sphere in a socket that enables a full 45 degrees of misalignment in any direction. This works with the receiver's gimbal feature described below to minimize moments applied to the USSV bow. The knuckle is designed to fail gracefully if damaged such that in the event of a collision the probe end will carry away at forces and moments below that which would damage the USSV. In addition, the knuckle's design will result in closing the liquid cargo pathway and allow the remaining probe to be retracted into the USSV bow. The knuckle only operates when the tensioned actuated valve is open, which only occurs when the probe end is pulled forward enough to overcome the spring force. When not opened the spring tends to keep the probe straight by pressing the tip onto the aft body, disabling the knuckle's function. If an excessive off axis force of say several hundred pounds is applied the probe end will be forced from the aft body and it will articulate and spring back to straight immediately after the off axis force is removed. Past probe systems independently developed by these authors struggled with the introduction of flexibility too much, and they would not enable a connection. Too little and they created large moments that increased structural strength requirements. The knuckle with tension actuated valve system presented herein solves this dilemma as it has both resistance to bending during engagement AND flexibility when under tension, achieving both in one simple configuration. The internal fuel passage is approximately ¾ inches in diameter nominally through the system and while there is plenty of cross section available, the pathway is somewhat tortuous with many expansions and contractions and sharp corners. Future versions could be refined if this proves to increase head loss beyond acceptable values.

3.6 Towed Sled

The sled comprises two sponsons connected at the forward end by a hinge, outriggers, a towing bridle, and other rigging and is presented in Figure 3. Commercially available foam filled High Density Polyethylene (HDPE) tubing was selected for the sponsons as they are practically unsinkable, rugged, and cost effective. In addition, the HDPE material is relatively soft in comparison to the USSV and host

vessel hull structure and will not scratch USSV or host vessel painted surfaces. Other advantages include easily removable bio fouling and relative ease of manufacture and repair via fusion welding. Each sponson is fitted with a flat bow plane set at a 30-degree angle and a counter cut away and tilted outboard by ten degrees. This configuration gave the best performance during model testing including a resistance to submerging and maintaining the open “V” formation when towed. The hinge comprises an aluminum weldment thru-fastened to the sponson’s side.

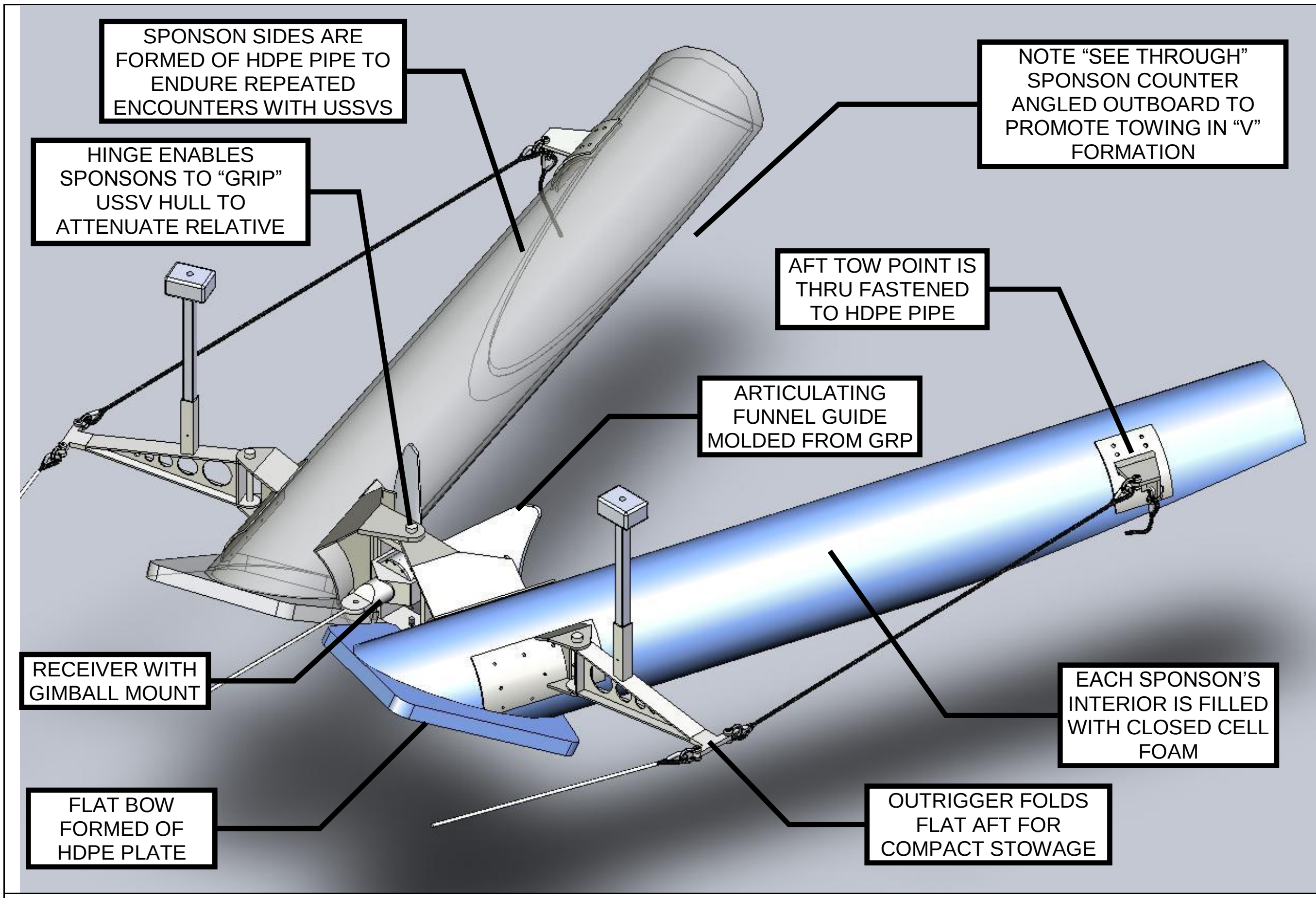

Figure 3. Towed Sled Comprising Specially Constructed Sponsons
Connected by a Hinge and Arranged to Tow in a “V” Formation of Sufficient Aperture.

When connected as an assembly the sponson floats with the hinge axis vertical and the two sponsons forming a horizontal “V” in the water. The towing bridle connects to the outboard ends of the outriggers which in turn are connected to the attachments near the aft outboard side of each sponson. The intent is that towing tension is used to maintain an open “V” form while towing, offering an adequate aperture for the USSV to enter from astern. A single line between the sponsons constrains the opening angle. The system is configured such that the USSV enters the wide open “V” from astern. As the USSV moves forward within the sled it encounters the intra sponson line. The USSV’s hull presses the intra sponson line deeper into the water and causes the sponsons to close up and “grip” the USSV’s hull, pressing the sponsons deeper into the sea and slightly lifting the USSV hull from the water. This contact serves to attenuate all relative motion, except surge, between the USSV hull and sponson, maximizing the likelihood of a successful capture. The outriggers described above are configured to fold

back along the sponson when stowed and with the sponsons hinged alongside one another, form a compact footprint for stowage and shipping.

3.7 Model Experiments

A towing model of the sled was evaluated to obtain a qualitative feel for the force balance required to maintain an open “V” formation across a range of speeds and to develop a configuration that will exhibit stable towing and resistance to submerging across a range of speeds. A model was constructed that replicated form and hinge function and included a towing bridle connected to outriggers and is presented in Figure 4. The model scale ratio was 1: 3.84.

Figure 4. Towed Sled Scale Model Demonstration.

These demonstrations comprised only the sled and did not include any vessel interaction other than the towing vessel’s wake. Observations were predominantly qualitative in nature except for towing tension, speed, and wind and sea and other meteorological conditions. The final configuration is the result of many iterations. The sled’s predicted full scale towing force will range from 400 and 700 pounds between 5 and 10 knots. An estimate for the combined sled and USSV tow force is presented in Table 2 below:

Table 2. Predicted Sled, USSV, and Total Towing Force as a Function of Tow Speed.

Speed	Tow Force, Pound		
Knot	sled	USSV	total
5.6	426	319	745
7.3	537	579	1116
8.6	635	860	1494

9.0	627	951	1579
10.3	628	1286	1914
11.2	681	1551	2232

3.8 Towing Hardware

The tow bridle connects the sled to the host vessel at the outriggers as described above and at the receiver. This comprises three legs connected to a single flounder plate some distance forward of the sled. Two legs are connected to the sled out riggers while a third leg is connected to the receiver. The legs connected to the outriggers are fitted with elastic take ups that are adjusted such that the majority of towing tension passes through two legs connected to the outriggers. This tension serves to keep the sponson open in the “V” configuration described above – the moments to open the “V” moving in lockstep with the total drag for a range of speeds. The central leg will have a small amount of slack when towing. After making a connection, the added drag of the USSV will elongate the elastics and the majority of towing tension will pass through the receiver. In addition to the tension members, a fuel hose connection will deploy alongside. The version used for testing also included an electrical umbilical but this was only employed during initial testing.

3.9 Receiver

The receiver comprises the probe latching mechanism, liquid cargo flow path and tension actuated valve, a gimbal mount, and the funnel guides. Sectional view is presented in Figure 5.

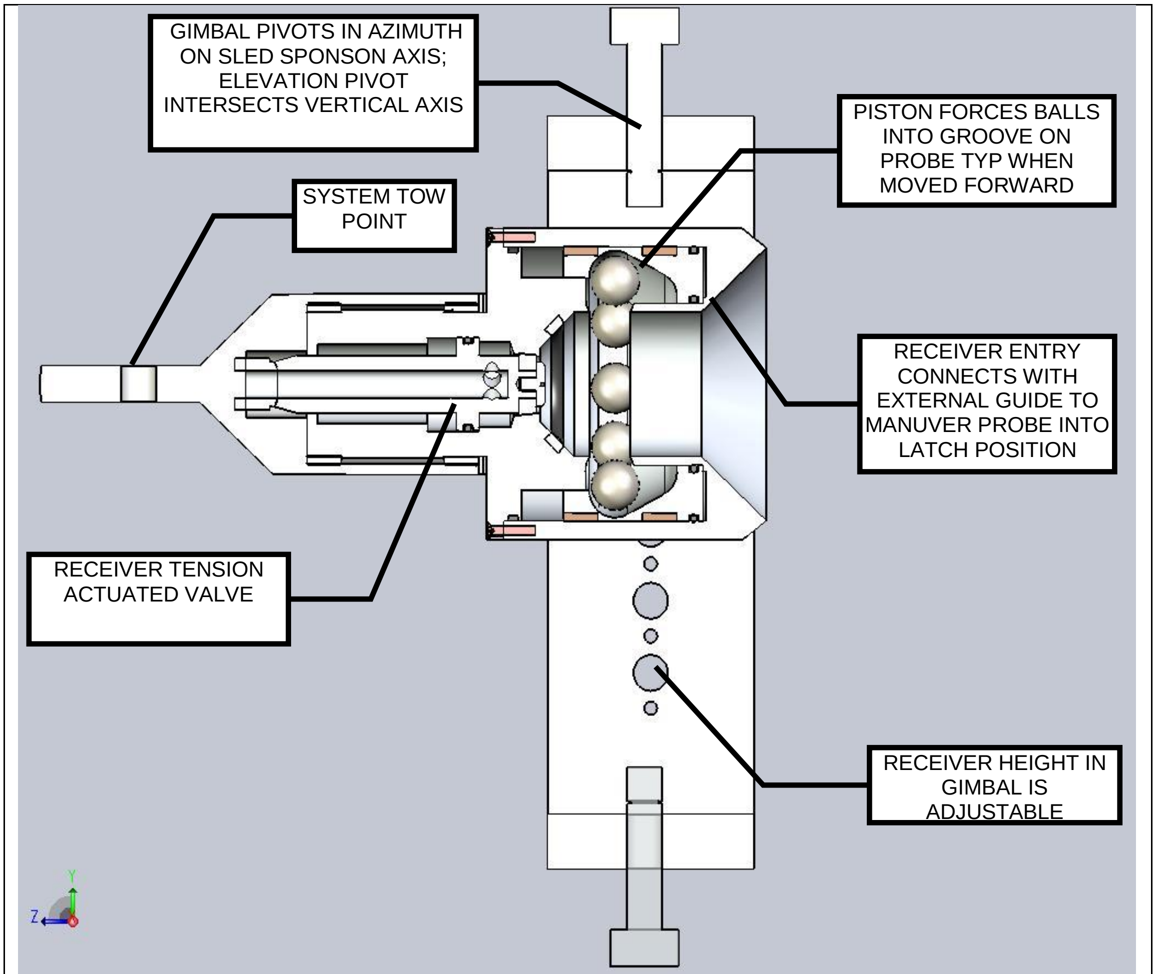

Figure 5. Receiver Cut Away Section Showing Internal Features.

The receiver latching mechanism operates not unlike an air hose ball detent connector. The ball latching method was selected over several other concepts relying on multiple pawls, roller cams, and other methods. The ball latching scheme has the advantage of permitting relative rolling motion and an insensitivity to roll angle during engagement. One ball latching challenge was the relatively high contact stresses that can be developed. The stress values calculated are relatively high in comparison to the material's strength. Classical analysis of these stresses are not well addressed by hertz or other methods as the groove diameter is very close to the ball diameter, and these methods are more geared towards contacts of curved surfaces that have greatly differing radii. The receiver latching mechanism consists of a housing with a set of steel balls in an annular cavity. The cavity has a slot that is slightly smaller than the ball diameter, and so serves to retain them. A piston with a conically tapered interior surface serves to press the balls through the slot and onto the probe. The piston is moved forward by hydraulic pressure to latch and aft to unlatch. An inductive proximity sensor mounted in the receiver detects the presence of the probe tip. This signal is used to initiate the latching process which comprises opening a three way hydraulic valve that admits oil pressure to the aft side of the above described piston, moving it forward and pressing the balls into the probe tip annular groove. The hydraulic pressure source comprises a small open loop power unit, a small accumulator, and solenoid, throttling, and relieve / charge / dump valves. Approximately 650 psi is required to withstand the 20,000 pound maximum towing force. When latched, the balls engage the groove in the end of the probe described above and hold it rigidly in position. The

balls are off the shelf units machined from 400 series stainless steel. At tow tensions greater than this the net force on the piston will over ride the hydraulics and the probe will disengage from the receiver. A second inductive proximity sensor detects the piston as it arrives in the full forward and latched position. The combination of the probe and piston sensors constitutes a successful latch.

The receiver is equipped with a tension actuated valve similar in design to that in the probe. This valve serves the same function of automatically closing the liquid cargo pathway the instant towing tension is lost. Energy to accomplish this is stored in a coil spring. Approximately 100 pounds of tow tension are required to crack and 120 to fully open this valve. The tension actuated valve status is sensed by a reed switch. The combination of the above mentioned successful latch criteria and valve opening constitutes the system being ready to test the cargo liquid pathway integrity and continuity. This is accomplished by applying compressed air at one end of the system and looking for a steady pressure at the other. A drop in pressure will indicate a leak somewhere. No pressure drop constitutes all seals in place and functioning correctly and, in combination with the above described successful latch and both probe and receiver towing tension actuated valves being opened, constitutes a readiness for fuel transfer to commence.

The receiver is mounted in a gimbal assembly that permits rotation about the vertical (azimuth) and athwart ships (elevation) axes. The azimuth axis is shared with the sled hinges and all axes intersect. The location of the receiver latching hardware is just forward of the axes of rotation and so thrust from the probe will tend to stabilize the receiver orientation during engagement. After the probe is latched to the receiver the forces are reversed, but the rigid tip will be connected to the above described knuckle joint well aft of the gimbal rotation axes and so will keep the receiver and probe tip stable under towing tension.

The receiver is fitted with an articulating funnel guide. This is formed from glass reinforced plastic (GRP) as two conic sections with horizontal axes. Each section is rigidly fastened to a sponson such that the combination forms a cone shaped guide with a wide opening facing aft and leading to the receiver as one moved forward. The angle is roughly 45 degrees and more or less matches with the slope of the front face of the probe. The port guide is fitted with a third conic section with a vertical axis and is arranged to maintain an unbroken and non binding guide structure while simultaneously permitting the sled sponsons to move relative to one another about their hinges. The funnel guide provides final guidance for the probe into the receiver and as such will encounter collisions of varying degrees. Solid laminate GRP was selected for these components for its toughness, flexibility, and ease of repair. If sea trials may indicate that greater collision resistance is required for these parts then a liner of HDPE or other material or compliant mounting may be required to increase longevity.

3.10 A Typical Refueling Scenario

A typical evolution would have the tow vessel and sled operating on a fixed heading and speed between 5 and 10 knots. A USSV will extend its refueling probe in preparation. The USSV will initially position itself approximately 100 or so feet astern and adjust its speed to gradually close the distance to the sled. USSV navigation will transition from the open sea absolute position system to a sled to USSV relative position system. The USSV will autonomously navigate and enter the open "V" and slow to an appropriate engagement speed and continue to advance forward into the sled until the probe makes contact with the receiver. The above described proximity sensor in the front of the receiver will detect

when the probe tip is fully seated and cause a relay to close and in turn energize the solenoid valve, connecting hydraulic oil pressure the receiver ball latch piston. Pressure will move the piston forward in the receiver and force the balls into the groove at the end of the probe, capturing it. A proximity sensor in the forward end of the receiver will sense when the piston has reached the latched position. The combination of both sensed signals indicates a successful latch. After the latching mechanism has been actuated, the USSV will slow to idle, shift to neutral, and center both rudders. The USSV will ride within the sled. Relative motion will be somewhat attenuated by the USSV riding onto the intra sponson line creating gentle contact as described previously. Remaining relative motion will be accommodated by the combination of probe knuckle joint and receiver gimbal articulation.

An unsuccessful latch would occur if the probe partially falls out of the receiver or piston does not reach its full travel. This could be caused by, for example, foreign matter on the probe preventing it from fully seating into the receiver. If this condition is detected the receiver will automatically disengage and allow the USSV to drift clear astern of the sled. After an appropriate delay, the USSV will autonomously engage its propulsion and re position for another attempt.

Presuming the latching was successful, compressed air will be introduced into the fluid piping between the sled and USSV mounted motor operated valves. A sensor connected to the USSV's fuel piping will detect the pressure, simultaneously validating that both receiver and probe tension actuated valves are in the open position and the seal between the receiver and probe is intact. At this point, liquid cargo can be transferred. A pump on the tow vessel will be plumbed to discharge into the umbilical hose connected to the sled.

At the completion of fuel transfer, the valves on the tow vessel and USSV will be shut. The fluid path may be blown down with air. The receiver will disengage the probe and the USSV will drift clear astern. At this time the USSV will autonomously engage its propulsion and resume its mission.

4.0 Conclusions

The data collection largely supports the short distance positioning system manufacturers' claim that their sensors provide relative position feedback of sufficient accuracy, quality, and latency that, when employed with the embarked control system components, enables the USSV HTF to be autonomously delivered to a moving target within +/- 0.5 m.

Looking at the data more closely, of all sea directions, test personnel observed that head seas proved to be the most conducive environment for autonomous run attempts. Head sea test runs provided for the highest percentages of close proximity run hits as well as more centered runs and the least amount of longitudinal offset. Even in sea state 2, head sea run attempts came nearer the center than any other sea direction. This might be explained by the greater resistance associated with advancing through head seas and wind requiring more throttle and consequently more prop wash over the rudders and so greater heading control authority or the wave energy being more or less aligned with the USSV's hull, thus not imparting yaw moments.

Stern sea test runs did not show any positive benefit for target proximity. Further, run attempts in stern seas demonstrated that the trend was for even more overwhelmingly starboard run directions than what was observed in other sea directions. The USSV HTF coxswain noted that during stern sea

runs, especially those runs performed within higher sea states, the impulse from the wave following the USSV HTF had the potential to push the USSV HTF so far forward that it collided with the target. This behavior happened several times. The data set provides for the more complex analysis of overshoot, and if performed this would shed more statistical light on the overshoot issues. However, manual observation was enough to see the enormous impact of an ill-timed swell pushing the USSV HTF significantly farther forward than the target wire distance. This could have significant implications of risk for autonomous run attempts behind the host ship in heavy seas, depending on what kind of run mechanism was in place.

The manual runs performed by the USSV HTF coxswain provides data to perform a comparison for the autonomous run attempts. These manual test runs had the best overall performance in head seas. It is interesting that even manual runs in head seas ranged up to 1 meter off from the target point. As such, the manual runs were proving to be just as accurate as the autonomous runs in head seas. The manual runs did demonstrate to be overall more centered than autonomous runs in head seas, however for beam seas and stern seas the manual runs were all impacting the imaginary plane on the starboard side. One important factor that the reader must bear in mind while reviewing the data within this document is that the run point and target point were both ‘virtual’ points. Therefore the only reference that the USSV-HTF coxswain had to aim for was a path down the centerline of the target with a sense of how close he was coming to it.

The overall high distribution of proximities to the target point demonstrates that there is room for refinement in the autonomous control algorithm. In its current configuration, the system performance in head seas is promising, but with significant concentrations of runs up through 1.25 meters, any run device would have to provide for a significant margin of error to account for this lack of accuracy. The amount of vertical difference between target points exceeded the amount of lateral difference by almost double in most instances. Pitch control has been a known issue from prior launch and recovery efforts. It is also the most difficult to correct as presently the USSV does not have a means to correct for pitch autonomously. A skilled coxswain may be able to influence pitch at a given instant, but that is long way from control. Based on the results from this investigation, a pitch induced relative vertical difference of over a meter is something that any recovery method needs to be able to tolerate for a high level of success.

Further, the fact that the USSV HTF drifted to the starboard on the vast majority of the runs, regardless of sea direction or state, indicates that tuning is required on some portions of the system. A large amount of data was recorded by test personnel during the execution of this test effort. This amount of data has potential to be analyzed in ways that are outside the scope of this test effort.

The foregoing conclusions were factored into the design of the towed sled refueling system. First, the “V” form has been configured for ranges that encompass the lateral positioning accuracy indicated above. As such we expect this system to have a very high rate of initial capture in which the USSV’s bow is successfully placed into the “V.” With regards to vertical positioning, the hull gripping concept described above in combination with final guidance via the articulating funnel guide will mechanically attenuate the relative motion and maximize latching success. Future sea trials will prove or disprove these theories. Sea trials of this system have not yet been accomplished as of this writing.

5.0 Recommendations

1. Extend this data set with a representative sample of each class of potential host ship/USSV combination to characterize how recovery operations are influenced by the addition of host ship wake and prop wash to the dynamic conditions. Use similar methods improved with lessons learned in the foregoing work. This is particularly important early in the development of a new class of USSVs or host ships.

2. Develop new and refine existing steering and control systems on USSVs that can assist with connection fidelity and precision requirements of recovery operations and equipment. Focus on reducing lateral offset including the development of new control laws and strategies and the adaptation of existing and/or development of new sensing technologies. Work should specifically target slow speed, high sea state capability and be capable of reacting to and taking appropriate action for normal and emergent recovery operation situations. USSV controls system intelligence should be capable of accepting, interpreting and making real time decisions about environmental information collected by on-board sensors or sensor systems external to the USSV.

3. Use information collected from prior testing of USSVs to help add realism to recovery software simulations and in the engineering design development of future equipment generations.

4. Continue testing and development of the single point connection refueling probe design. Review testing results to evaluate if the probe size (and corresponding bow plug size) reflects the capture percentage desired for unmanned refueling operations.

6.0 References:

1) Eisenberg, Kedric C. "Development and Evaluation of USSV Recovery Mechanism, ASNE Launch and Recovery Conference, November 2005.
2) Galway, Robert, "Design Considerations for Autonomous Launch and Recovery of Autonomous Unmanned Surface Craft", ASNE Launch & Recovery Conference Paper, May 2008.
3) Galway, Robert, Autonomous Refueling of Unmanned Vehicles, ASNE Launch and Recovery Conference paper, May 2008.

7.0 Acknowledgements

The authors acknowledge NWSCCD C235 Test and Evaluation personnel and WRSystems for support with development of the data collection test method, test equipment, and data collection. A further acknowledgement is extended to WRSystems for support with report preparation. The authors also acknowledge CDI Marine company's contribution to the design and fabrication of the new probe/receiver/sponson system, in particular Brandon Lukert, Johnny Lassiter, Gordon Hatchell, John Melnik, and Dan Sykes. This work was funded by the Office of Naval Research, Sea Platforms and Weapons Division.